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A review of wireless communications for smart grid

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ABSTRACT

Smart grid is envisioned to meet the 21st century energy requirements in a sophisticated manner with real time approach by integrating the latest digital communications and advanced control technologies to the existing power grid. It will connect the global users through energy efficiency and awareness corridor. This paper presents a comprehensive review of Wireless Communications Technologies (WCTs) for implementation of smart grid in a systematic way. Various network attributes like internet protocol (IP) support, power usage, data rate etc. are considered to compare the communications technologies in smart grid context. Techniques suitable for Home Area Networks (HANs) like ZigBee, Bluetooth, Wi-Fi, 6LoWPAN and Z-Wave are discussed and compared in context of consumer concerns and network attributes. A similar approach in context of utilities concerns is adopted for wireless communications techniques for Neighborhood Area Networks (NANs) which include WiMAX and GSM based cellular standards. Smart grid applications, associated network issues and challenges are elaborated at the end.

Contents

1. Introduction

The present electricity infrastructure is a complex and aging system characterized by centralized power generation and distribution, one

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way power flow and lack of user–utility interaction which leads to energy loss, overload conditions, power quality issues, poor peak load management, lack of renewable energy usage, time wastage and manual operational processes. This along with foreseen decline in fossil fuels availability, rise in fuel cost, related environmental issues like global warming from greenhouse emissions and rising demand for electricity require re-envisioning of the traditional electricity grid [1,2].

Consumers around the globe need the continuous and reliable energy supply in a cost effective manner. Power quality and environmental concerns are important as well. Global consumers' general concerns are depicted in Fig. 1 which may vary according to the regional situations and requirements of the consumers. Smart grid is envisioned to fully address these concerns in a sophisticated and dynamic way.

Rapid advancements in control, Information and Communications Technologies (ICTs) have allowed the conversion of traditional electricity grid into smart grid that ensures productive interactions among energy providers (utilities), consumers and other stakeholders [3]. These multiple and enhanced interactions, shown in Fig. 2, will help solving the issues raised in existing grid.

Key components of smart grid are smart meters, sensors, monitoring systems and data management systems that control the flow of information among various stakeholders, making it a two way communications network, also called Advanced Metering Infrastructure (AMI) [4]. Other smart grid applications include Energy Management Systems (EMS), Distributed Power Generation (DPG) and its reliable integration to the system, equipment diagnostics, control, overall optimized asset management etc. Plug in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs) have important effects regarding reliability of grid. Effective management of EVs is also an important area of smart grid and needs intensive research. All of these applications strongly rely on communications infrastructure. Home Energy Management System (HEMS) requires a short distance network, called Home Area Network (HAN). Communication between users and utilities needs a Neighborhood Area Networks (NAN) and may also need a Wide Area Network (WAN). Our objective is to explore various short and long range communications technologies that can be applied to key smart grid applications.

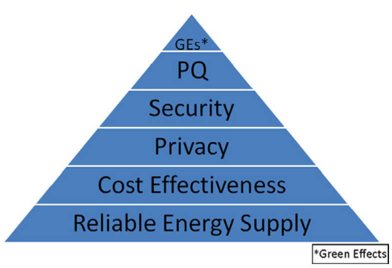

Fig. 1. Global consumers' concerns.

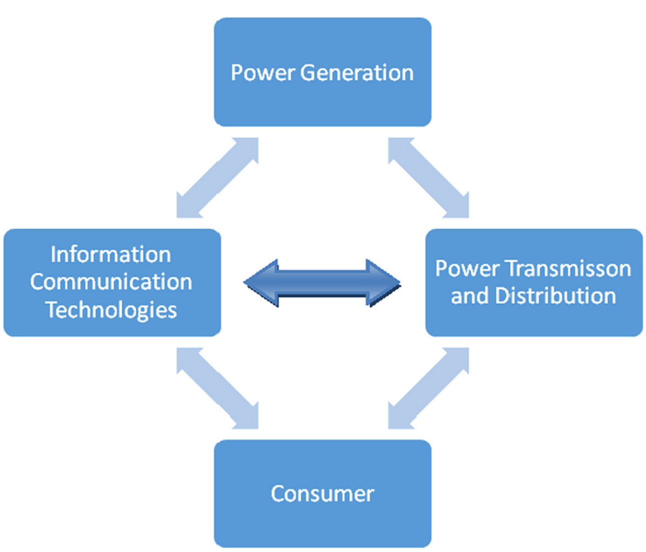

Fig. 2. Multiple interactions among major stakeholders of smart grid.

There are two different sets of communications technologies based on wired and wireless media. Each of these technologies has its own advantages and disadvantages that vary according to nature of application. IEEE and many other regional and international bodies have identified a number of wired as well as Wireless Communications Technologies (WCTs) in smart grid applications. However, in many smart grid applications the sheer number of communications links makes the use of wired solutions economically and/or physically prohibitive. On the other hand wireless technologies offer benefits such as lower cost of equipment and installation, quick deployment, widespread access and greater flexibility [5,6].

In literature, numerous examples have been reported about research on communications technologies for smart grid. An overview of ICT suitable for smart grid applications has been presented in [7], a discussion on various contemporary standards available for smart grid as well as proposition of a quality of service (QoS) mechanism makes it a nice contribution to smart grid literature. Various wireless communications options for smart grid applications have been presented and challenges associated with each wireless technology are discussed in [8]. The main feature of this work is evaluation of wireless LAN (WLAN), WiMAX, Cellular and ZigBee technologies for suitable smart grid applications. A wireless communications scheme for AMI is proposed in [9] which is based on an experiment that provides real time power consumption of households. The experiment implies that such consumption follows Poisson distribution. The proposed communications scheme takes into account the Poisson nature of power consumption to implement AMI wireless communication infrastructure using different multiple access technologies. A cloud computing model for development of smart grid solutions is presented in [10] in which delivery of computing is introduced as service. Advantages of cloud computing like cost saving, increased flexibility, storage capacity and on demand performance are described in context of utility concerns. Mathematical modeling of packet arrival process along with security considerations makes this research even more useful. In [11], different candidate communications technologies for HANs have been compared with emphasis on Demand Side Management (DSM) and dynamic pricing. Various factors affecting the choice of wired and WCTs have been discussed, which provide a comparison basis in different scenarios. A smart grid communications architecture is proposed in [12] which operates in three different modes i.e. distribution level, relay control level and home level. Authors employed the latest WCTs for the proposed network architecture and experimented with remote monitoring, high rate transmission and also for video on demand. Application of the latest WCTs showed high performance for smart grid applications in terms of frame error rate, delay etc.

Efforts have also been made to explore suitability of specific communications technologies for smart grid applications. For instance applications of ZigBee for smart grid have been mentioned in [13] where ZigBee has been compared with Wi-Fi and Bluetooth as well as prospects of ZigBee for HANs and other smart grid applications are investigated. Authors also considered the use of ZigBee along with long range wired and wireless communication technologies for a more practical communications scenario. Sensors are an integral part of smart grid and wireless networks

involving sensors have been heavily investigated by researchers. For instance, ZigBee has been compared with IP in [14] in the wireless sensor network context and some of the limitations of ZigBee in certain scenarios have been discussed. Since IP is not supported in earlier versions of ZigBee, IP-based services could not be used along with this technology. The discussion on this problem and possible solutions for ZigBee and IP coexistence make this piece of research useful for smart grid researchers. Suitability of ZigBee for power monitoring and control has been demonstrated in [15]; various operating mechanisms and network architectures give an insight to power monitoring and control using different Wireless Communications Technologies. Wi-Fi technology for smart grid sensor networks has been explored in [16]; Wi-Fi advantages over ZigBee, when large data rate is required, have been described. This research is more relevant to special smart grid applications with high bandwidth/data rate requirements such as video monitoring. A comparison of communications technologies available for smart grid NAN has been presented in [17]; the authors concluded that WiMAX and LTE are more suited to smart grid NAN compared to other contenders based on experimental results showing low latency and low packet loss for these technologies. In this piece of work, a certain smart grid distribution network is used to simulate the different wireless technologies. This along with QoS and scalability considerations is one of the main features of their work. The authors in [18] proposed a voltage control scheme that uses WiMAX in order to communicate voltage levels and optimizes the voltage with minimum communications cost. This work uses a probabilistic model to implement one of the key smart elements in an electric grid i.e. voltage control. WiMAX application on automatic meter reading in terms of delay, throughput and size of the network has been investigated in [19]. The main contribution of this research is OPNET models used to simulate WiMAX network configurations for smart grid meter reading application. A Radio Frequency (RF) mesh based model has been presented in [20] for smart metering application where the performance of the model in terms of reliability and failure preemption is taken into account. The main feature of this piece of research is description of various use cases of RF mesh simulated with a discrete event simulator. The authors in [21] proposed a Global System for Mobile Communications (GSM) and Short Messaging Service (SMS) based communications system to control EVs charging. The major benefit of the work is a mechanism for effective variation of prices resulting in avoidance of extraordinary peak loads. Researchers have also discussed the coexistence of smart grid and cellular networks as well as the associated benefits in terms of power usage and green effects [22]. Evolution of the smart grid communications technologies has been presented by Ahmad et al. in [23] that covered different wired and wireless technologies. However, we have reviewed and compared WCTs along with key applications and challenges of the smart grid.

We need to compare some major available WCTs for optimized asset management in smart grid. There are two major areas of application for smart grid: indoor and outdoor. It should be noted here that HANs need short range, low data rate and low power wireless technologies to be used within households while NANs require relatively long range, high data rate and secure communication in order to exchange control and data signals among utilities and consumer premises.

This paper discusses the wireless communications for smart grid and analyses the extent to which the standardized communications technologies to meet the requirements of individual smart grid applications based on spectrum, coverage distance, data rate and other significant parameters. The discussion on wireless communications has been divided into two categories: wireless communications for HANs and wireless communications for NANs. Advantages and disadvantages of using a certain communications technology for a certain smart grid application have been discussed. Smart grid applications are described in the light of wireless communications technology. Challenges for the realization of smart grid are elaborated before conclusions. Paper is organized in such a way that concept and introduction of smart grid along with literature review is covered first. This is followed by the discussion of wireless communications for HANs and NANs and their comparative study. Applications and advantages that can be achieved by implementation of smart grid are described separately and finally the challenges and issues related to smart grid implementation are briefed. Paper organization is summarized in Fig. 3.

Remaining sections are sequenced as follows. Wireless communications and their comparison for smart grid are discussed in Sections 2 and 3 respectively. Smart grid applications are elaborated in Section 4. Challenges and issues for realization of smart grid are elaborated in Section 5 before conclusions in Section 6.

2. Wireless communication options for HANs

This segment investigates suitability of different short range wireless communication protocols for smart grid HANs implementation. ZigBee, Bluetooth, Wi-Fi, 6LoWPAN and Z-Wave are the technologies to be discussed. IEEE has set different standards for first three of these technologies in which only the Physical (PHY) and Medium Access Control (MAC) layers are defined: Bluetooth (802.15.1a), ZigBee (802.15.4b) and Wi-Fi (802.11g). Internet Engineering Task Force (IETF) has introduced 6LoWPAN standard in order to achieve IPv6 enabled low power communications. Z-Wave, a proprietary solution, is also considered for comparison purpose. One of the major goals of this work is to provide a comparison basis for the main WCTs to be used in HANs in the smart grid context. WCTs for HANs are discussed in detail in the following sections.

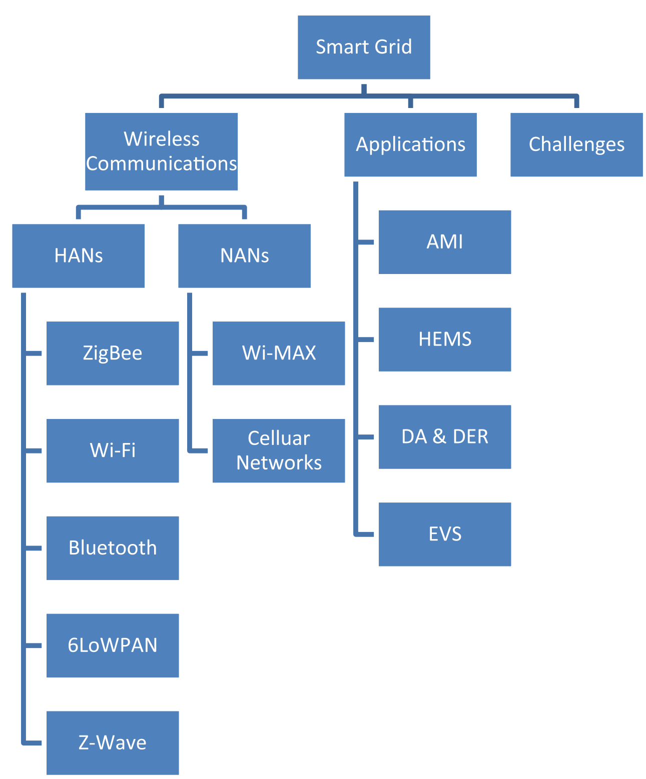

Fig. 3. Paper organization.

2.1. ZigBee

ZigBee [24,25] is a wireless mesh network, built on the IEEE standard 802.15.4, is very efficient and cost effective solution. However, it offers low data rate for Personal Area Networks (PANs). This technology can be used broadly in device control, reliable messaging, home and building automation, consumer electronics, remote monitoring, health care, and many other areas. It is a low power network provided all devices are interconnected by IEEE 802.15.4 links with Direct Sequence Spread Spectrum (DSSS). Estimated data rates are 250 kbps per channel in the unlicensed 2.4 GHz band, 40 kbps per channel in the 915 MHz band and 20 kbps per channel in the 868 MHz band. ZigBee supports 10–75 m point to point, typically 30 m indoor and unlimited distance with mesh networking. In a mesh network each node can be reached by multiple links and connections are dynamically updated and optimized. Mesh networks are de-centralized and each node can manage itself in the changing conditions and is able to dynamically self-route and connect with new nodes as needed. These features offer scalability, greater stability and tolerance against node/link failures. This along with low power utilization and low deployment cost makes ZigBee very attractive for the smart grid HAN applications.

ZigBee Alliance, an association of companies offering wireless solutions, has offered many standards to suit different set of requirements. These standards include ZigBee Building Automation, ZigBee Remote Control, ZigBee Smart Energy, Smart Energy Profile 2, ZigBee Health care, ZigBee Home Automation, ZigBee Input Device, ZigBee Light Link, ZigBee Telecom Services and ZigBee Network Devices. Smart Energy Profile 2 (SEP2) offers IP functionality which enables large scale multi-vendor deployment of smart meters, sensors, smart appliances and energy displays etc. This will also allow communicating with IPv6 based nodes using other network architectures like Wi-Fi, Ethernet etc. offering ever greater interoperability and compatibility.

ZigBee, a type of micro-power wireless communications technology, is supported by IEEE 802.15.4 standard that defines PHY and MAC layers. IEEE specifications are used by ZigBee Alliance for structural expansion of network layer and application layer. A ZigBee network uses three types of nodes: ZigBee Coordinator (Full Function Device, 'FFD'), ZigBee Router (FFD) and ZigBee End Device (Reduced Function Device, 'RFD') [7]. ZigBee Coordinator initiates session and manages the security. Beacon and non-beacon enabled networks are supported in ZigBee protocols. In beacon-enabled networks, the special network nodes (such as ZigBee Routers) broadcast cyclic signals for verification of their existence to other nodes. It helps receiving/transmitting data and increases efficiency of the network. In non-beacon-enabled networks ZigBee Routers have their receivers continuously active, involving a more vigorous power supply. Beacon intervals depend on data rate, at 250 kbps 15.36 ms to 251.65824 s, at 40 kbps 24 ms to 393.216 s and at 20 kbps 0.48 s to 786.432 s [13]. ZigBee uses access control list or Advanced Encryption Standard (AES-128) to guarantee a high-level security.

2.2. Wireless Local Area Network (WLAN) and Wi-Fi

WLAN, based on IEEE 802.11, employs the spread spectrum technology so that users can occupy the same frequency bands while causing minimal interference to each other. Networks based on 802.11 are most popular for LAN usage with maximum data rates of 150 Mbps and maximum coverage distances of 250 m [26]. WLAN also known as Wireless Ethernet is able to provide robust communications with low latency and capable of point-to-point as well as point-to-multipoint transmissions. Wi-Fi (802.11b), operating on 2.4 GHz with DSSS modulation, gives maximum data-rates of 11 Mbps with a latency of 3.2–17 ms [26]. Other technologies like those based on IEEE 802.11a, which operates on 5.8 GHz using Orthogonal Frequency Division Multiplexing (OFDM) and IEEE 802.11 g (enhanced Wi-Fi), operating on 2.4 GHz with DSSS modulation, increase obtainable data rate to 54 Mbps. Data rates of up to 600 Mbps can be obtained via 802.11n which uses Multiple Input–Multiple Output (MIMO) scheme. Security issues for WLANs are addressed in IEEE 802.11i (WPA-2) which uses the Advanced Encryption Standard [8].

Wi-Fi is a more popular name for certain 802.11 based technologies used in HANs, mobile phones, computers and many other electronic devices. Wi-Fi technologies include 802.11n (300 Mbps), 802.11b (11 Mbps), 802.11g (54 Mbps) and 802.11a (54 Mbps). Its main feature is existing wide support; almost every new electronic device, be it a computer, laptop, game console or a peripheral device comes with Wi-Fi technology. Wi-Fi is generally upper layer protocol with IP being the most predominant protocol, allowing communications over the internet without needing a protocol translator. A non-profit international association of various businesses/companies, Wi-Fi Association, formed in 1999, works to support and maintain Wi-Fi technology.

Channel assignment for Wi-Fi is not consistent across the globe. For example, the number of assigned channels is 11 in the USA, 13 in Europe and 14 in Japan. Only a limited number of channels may be used without any overlap which means a limited number of devices can be connected in a Wi-Fi Wireless Local Area Network [27]. This interference along with security issues are the big challenges in using Wi-Fi for the smart grid HAN applications. However, advantage of Wi-Fi lies in high data rate, IP support, wide spread availability and scalability [16].

WLAN/Wi-Fi is more suitable for applications with relatively smaller data rate requirements and low interference environments. Ethernet based communications for interoperable substation automation systems have been suggested by IEC 61850 standard. IEC 61850 based WLAN can boost the protection of distribution substations via intelligent monitoring and control using sensors and intelligent controllers with wireless interfaces. IEEE Power System Relaying Committee reports intra-substation applications like enhanced transformer differential protection through the use of wireless Load Tap Changer (LTC) sensors. Communications for Monitoring and Control at substations can be made more reliable via usage of redundant wireless links alongside optical fibers. WLAN (Wi-Fi) with intelligent sensing and control devices may also be used in differential protection applications. It is possible to develop a dynamic self-organizing, self-healing network by combining WLAN with Wireless Mesh concepts. Wireless-Mesh uses multi-hop routing for greater coverage distances with low transmission powers [28]. Smart meters with Wi-Fi modules may be used for signal repetition and addition of repeaters increases the coverage area and network capacity [7]. WLAN can provide the aforementioned services for both Distributed Energy Resources (DERs) and distribution substations. There are various challenges when dealing with WLANs such as

- electromagnetic interference: because high voltage electrical equipment can slow down communications or even can vanish out the signal entirely,
- interference from other wireless equipment: will have unfavorable effects on communications, and
- Wireless equipment for Industrial environment is not readily available.

However advancements in acknowledgment protocols, algorithms for error correction and buffering of data have increased the reliability of wireless communications. Developments like Smart Antennas and waveguides have made it possible to combat

Table 1
Comparison of HAN technologies for smart grid.

	ZigBee	Wi-Fi	Bluetooth	6LoWPAN	Z-Wave
Max. speed per channel	250 kbps (2.4 GHz) 40 kbps (915 MHz)	11–300 Mbps	Max. 1 Mbps	250 (2.4 GHz) 40 kbps (915 MHz) 20 kbps (868 MHz)	40 kbps
Reach	10–75 m	100 m (indoor)	10 m typical	Up to 200 m	30 m indoor, 100 m outdoor
Standard	IEEE 802.15.4	IEEE 802.11	IEEE 802.15.1	IETF RFC 4944	Proprietary
IP support	IPv6 only in SEP2	IPv6	Not presently, research continues	Yes, IPv6	Yes
Adoption rate	Widely adopted	Extremely high	Extremely high	Medium	Medium
Unique value	Low cost, low power usage, high number of nodes	High speed mature standards	Ease of access, no configuration requirement, secure connection	Benefits of both IP and Bluetooth, low power consumption	No interference from household devices

Radio Frequency and electromagnetic interference for production of better WLAN devices [8].

2.3. Bluetooth

Bluetooth [29,30] is another common wireless communications system used to exchange data over short distances. It employs short wavelength radio transmission in the Industrial, Scientific and Medical (ISM) band (2400–2480 MHz). Its main features are low power consumption and fast data exchange as well as wide spread availability. Bluetooth technology was developed by engineers at Ericsson in 1994. Later a group of companies started using Bluetooth and made a special interest group (SIG) to maintain and enhance this technology. The IEEE standard for Bluetooth is IEEE 802.15.1.

There are two topologies used in the Bluetooth i.e. Piconet and Scatternet. A Piconet is formed by a Wireless Personal Area Network (WPAN) in which a mobile device is acting as a master and other mobile devices will be serving as slaves. A Scatternet consists of two or more Piconets. Bluetooth can be used for communications among smart home appliances, EMS and the smart meter. It has maximum data rate is 1 Mbps, nominal range of 10 m, 79 RF channels, 1 MHz channel bandwidth and max of 8 nodes. Bluetooth has three classes i.e., Class 1, Class 2 and Class 3 each having a different range.

Bluetooth has very short range which can be a problem when using this technology in smart HANs, as longer distances may be involved. Moreover, it supports limited number of nodes that can be a serious constraint in HANs. Bluetooth, like many other technologies is operated at low power which means the strong noise can cause signals to be lost or damaged. Moreover, it works on 2.4 GHz and has interference issues with other wireless technologies like Wi-Fi, ZigBee etc. with same system frequency. Furthermore, Bluetooth has some inherent security issues [31]. On the other hand, the most recent version of Bluetooth v4.0 has introduced low energy technology. This low energy technology is being investigated by researchers for IP support. See for instance [32] where the authors have implemented Bluetooth low energy connectivity with IPv6 support.

2.4. 6LoWPAN

6LoWPAN is the IETF working group formed in 2005. It enables IEEE 802.15.4 (IEEE subcommittee for low rate WPAN) and IPv6 to work together in order to achieve IP enabled low power networks of small devices including sensors, controllers etc. IETF RFC 4944 describes the mechanism of combining IP and WPAN technologies. The authors in [33] analyzed 6LoWPAN along with IPv6 for home automation networks. They used a web interface in order to manipulate home appliances and described usefulness and challenges of IPv6 and 6LoWPAN in this regard. A smart grid specific discussion on IPv6 and 6LoWPAN application is presented in [34] where the authors emphasized on memory management and portability challenges. Various technology vendors are trying to adopt 6LoWPAN based protocols in order to achieve IP functionality. For instance, ZigBee Alliance has developed an IP network specification, ZigBee IP, which is based on IETF protocols including 6LoWPAN.

6LoWPAN uses mesh topology to support high scalability. The scalability is also affected by choice of routing protocols. For instance, hierarchical routing is one of the routing protocols used in 6LoWPAN to increase the network scalability [35]. Mesh topology also offers the self-healing capability to the network as the traffic can be re-routed in case of a broken link. 6LoWPAN offers high interoperability as IP is supported in most of the modern technologies. An investigation of interoperability of 6LoWPAN-based web applications can be found in [36]. Security of 6LoWPAN is one of the challenges faced by researchers and there are ongoing efforts on improving security level. See for instance [37] where IPSec is used along with IP to enhance 6LoWPAN security. The authors in [38] have compared link-layer security and IPv6 security for 6LowPAN.

2.5. Z-Wave

A proprietary standard intended exclusively for remote control applications in residential and business areas is given the name of Z-Wave. This protocol works at 868 MHz in Europe and 908 MHz ISM band in USA. It has typically 30 m indoor range which extends up to 100 m outdoor. Mesh networking is employed in Z-Wave which essentially means unlimited range. The main advantages of this technology come from simple command structure, freedom from house hold interference, low bandwidth control medium and IP support.

Z-Wave offered a low data rate of 9.6 kbps; however it was extended to 40 kbps later on [39]. Z-Wave 400 series also supports 2.4 GHz band and 200 kbps data rate [40]. Z-Wave automatically routes the message from one node to the other because of the routing capability of all the nodes. Controllers and slaves are two types of devices defined by Z-Wave. Controller maintains the network topology. Slaves can also be used as routers and are useful for monitoring of sensors.

2.6. Comparative study

Comparative study of ZigBee, Wi-Fi, Bluetooth and 6LoWPAN reveals that Wi-Fi has advantages of larger coverage and widespread availability, Bluetooth is easily accessible and provides secure short range communications, 6LoWPAN adds IP functionality to WPANs and consumes low power while ZigBee accommodates much more nodes, operates at low power and requires low cost. ZigBee can be used in HANs, as well as for smart

metering if used in a mesh structure. It can also provide remote monitoring of the smart meter and other devices. ZigBee has reliable security and employs powerful encryption techniques. It has far superior networking technique compared to other technologies which avoids the channel collision. On the other hand, 6LoWPAN is suitable for IP enabled low power devices like sensors and controllers. Z-Wave is characterized by the reliable transmission of short messages from controller to one or more nodes. The main attributes of these technologies have been summarized in Table 1.

One of the major features of smart grid is bi-directional flow of information and power among users and utilities. Achievement of this feature requires larger networks or NANS. Wireless communications for NANs are discussed and compared in Section 3.

3. Wireless communication options for NANs

Communications among energy utilities, smart meters, HANs, DERs and other possible smart grid entities requires a large network with appropriate network architecture and communications technology. Our objective in this section is to explore and compare communications technologies available to fulfill smart grid NAN requirements. Some of the NAN technologies are discussed in the following sections.

3.1. WiMAX

WiMAX, one of the standards from IEEE 802.16 series designed for Wireless Metropolitan Area Network (WMAN), aims at achieving worldwide interoperability for microwave access (2–66 GHz). WiMAX is characterized by low latency (<100 ms for round trip), proper security protocols (AES, AAA, etc.), lower deployment and operating costs, scalability [7] and availability of traffic management tools (traffic prioritization, quality of service, etc.). Developing WiMAX based architecture requires developing a utility-proprietary network having total control of traffic management and capable of coping with regular and emergency conditions [28]. The bandwidth and the range of WiMAX allow its use for smart grid NANs successfully [17]. For example, WiMAX can be used for the following:

- Wireless Automatic Meter Reading (WAMR): WiMAX technology is suitable for WAMR as part of a utility's AMI network as it offers efficient coverage and high data rates.
- Real Time Pricing (RTP): WiMAX based AMI can easily be employed for provision of real time price signals to the consumers based on their real time energy usage.
- Detection and Restoration of Outage: Using bi-directional WiMAX links, outages can be quickly detected and power restored resulting in increased reliability of power supply.
- Monitoring: Sensor data can be transmitted over WiMAX links for monitoring purposes.

There are certain challenges associated with WiMAX. For instance, WiMAX towers are based on relatively costly radio equipment, care must be taken to ensure optimal locations are chosen so that infrastructure expenses are reduced and QoS requirements are met. WiMAX frequencies >10 GHz are unable to pass through obstacles, hence lower frequencies are better suited for advanced metering applications particularly for urban areas. Since the lower frequency bands are already licensed, leasing from third parties may be required [8].

3.2. Cellular network communications

2G, 2.5G, 3G and Long Term Evolution (LTE) are potential cellular communications technologies which can be used for smart grid communications. Data rates have evolved from 14.4 kbps for 2G – GSM to 56–171 kbps for 2G – GPRS (General Packet Radio Service), to 2 Mbps in 3G and recently to 50–100 Mbps for 4G – LTE [12]. Using pre-existing cellular networks saves investments on utility dedicated communications infrastructure and allows rapid deployment of applications. Sufficient bandwidth, high data rates, extensive coverage, lower maintenance costs and strong security are enabling features of present day cellular networks.

An embedded network operator Subscriber Identification Module (SIM) or GPRS module inside a cellular radio unit integrated in smart meters can enable communications among smart meters and utilities. Since the network operator's GSM/GPRS network can handle communications requirements for smart metering network, utilities can concentrate on applications and services. GSM and GPRS provide users with anonymity and protection of their data alongside authentication and signaling protection for security. Numerous cellular network operators around the world have already approved to put GSM networks into service for AMI communications [7]. Developing Smart grid Communications network for EVs is possible by using GSM network and SMS messages [21].

Based on GSM/EDGE (Enhanced Data Rates for GSM Evolution) and Universal Mobile Telecommunications System (UMTS) technologies, LTE is one of the latest developments in wireless communications field. This wireless communications standard provides high speed data transfer (up to 300 Mbps download and 75.4 Mbps upload depending on technology used) with low latency. The first commercial deployment of LTE was experimented in Oslo and Stockholm in December 2009. It uses OFDMA and Single Carrier Frequency Domain Multiple Access (SC-FDMA) in order to use minimum power and supports various cell sizes (10 m to 100 km). LTE is fully compatible with other legacy standards like GSM/EDGE, UMTS and CDMA2000 etc. The latest form of LTE, known as LTE Advanced, offers approximately 3.3 Gbps download speed. The LTE Advanced is also in commercial use since October 2012. 3G and 4G – LTE cellular technologies operate on the licensed frequency range of 824–894 MHz/1900 MHz [8]. Large network operators widely support LTE while chipset manufacturers are expected to reduce prices associated with LTE hardware [28]. Some mission-critical applications require continuously available communications. Services of cellular companies are also used for customer markets which could result in congestion issues or reduced network efficiency for emergency scenarios [7]. Emergency communications vehicles acting as base stations can be used in these situations. LTE can also fulfill the throughput, error-rate and latency requirements for emergency situations [28].

LTE has two major application areas in smart grid. First it can be used for automated metering and secondly for automating and controlling the distribution system. The authors in [41] analyzed the application of LTE for automated electricity distribution systems and found that this technology is feasible for NAN smart grid applications with high reliability and low latency. LTE application for both automated metering and automated distribution is analyzed in [42].

Using third party networks means monthly recurring charges for every connection which translates into greater operating costs for the utility. To ensure quality and reliability of service and avoid added operating costs, a utility may decide to build dedicated cellular networks [7]. Cellular networks can be used to

- provide communications for wide area smart applications like Automated Demand Response (ADR), AMI and outage management [7],

Table 2
Comparison of NAN technologies for smart grid.

	WiMAX	2G – GSM	2.5G – GPRS	3G – UMTS-CDMA2000-EDGE	4G – LTE
Max. speed per channel	72 Mbps	14 kbps	171 kbps	More than 2 Mbps	300 Mbps, 3.3 Gbps for LTE advanced
Reach	9 km	10 km	10 km	10 km	10 km
Adoption rate	Widely adopted	Extremely high	Widely adopted	Widely adopted	Widely adopted
Unique value	Low cost, low latency	High Adoption, extensive coverage	Uses GSM network but supports data transmission	High data rate	Extremely high data rate
Applications	AMI, ADR	AMI, EVs, ADR	AMI, EVs, ADR	DERs, AMI, EVs, ADR	DERs, AMI, EVs, ADR

- provide communications between Remote Terminal units (RTUs) at substations and the SCADA server at the utility [8],
- provide communications to enable supervision of remote DERs. Non-critical information may be communicated via SMS messages and DERs can be monitored with GPRS systems [8].

3.3. *Comparison of wireless NAN technologies*

Bandwidth and the range of WiMAX make it appropriate for smart grid NANs applications. However, pre-existing cellular networks with sufficient bandwidth, high data rates, extensive coverage, lower maintenance costs and strong security can save capital investments on utility dedicated communications infrastructure and allow rapid deployment of applications. However, use of pre-existing cellular networks will raise the operational cost in terms of monthly recurring charges. A dedicated utility cellular network can ensure the high quality and reliability with reduced operational cost. This comprehensive review has tabulated different wireless communications in a systematic way along with the challenges for smart grid implementation. A comparison of NANs wireless technologies is summarized in Table 2.

Wireless communications discussed and compared in Sections 2 and 3 can be employed for various smart grid applications. Some of the major applications like AMI, HEMS, Distribution Automation (DA), DER and EVs are detailed in Section 4.

It is evident from Sections 3 and 4 that HANs and NANs have very different communication requirements. The operating environment, coverage range, data rate and security requirements are particularly different. Wi-Fi, ZigBee, Bluetooth, 6LowPAN and Z-Wave are quite suitable for HANs. ZigBee may be preferred because of supporting a large number of nodes and low power consumption. 6LowPAN or Z-Wave may be employed in order to achieve IP functionality. Wi-Fi may be considered due to its high data rate for some advanced applications (e.g. video monitoring). On the other hand, WiMAX and GSM-based networks offer many benefits to NANs such as high data rate (to support bulk communication among utility and a high number of consumers), greater coverage range and advanced security protocols. The choice between a utility owned dedicated network and pre-existing cellular network depends on a particular utility's policies, budget etc.

4. Smart grid applications

This section is dedicated for smart grid applications. Advanced ICT has converted the world into a global village. It may be expected that implementation of the smart grid will ultimately connect the global users through energy efficiency and awareness corridor. Smart grid has many applications like AMI, DA, HEMS, EVs management, integration of Distributed Generation (DG) from renewable energy resources in an efficient and reliable way etc. Some of these applications are discussed in detail in the following sections.

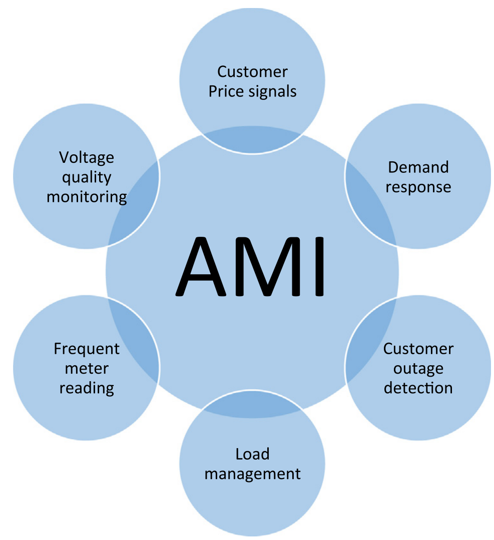

Fig. 4. AMI features.

4.1. *AMI*

A bi-directional communications network made by the integration of various technologies such as smart meters, HANs, advanced sensors, control systems, standardized software interfaces and information management systems to allow the gathering and dissemination of information between user-end and utilities is known as AMI. These technologies are further integrated with existing utility operations. AMI has potential to provide utilities with data related to energy consumption for billing purposes, data on power-quality, voltage and load profiles. Obtaining this data through AMI will eliminate the need for field trips of personnel for meter reading, manual outage reporting and most restoration operations. In other words, it will provide remote meter management (remote connect/disconnect) and outage detection. Via AMI, utilities and customers will be in constant contact thus enabling utilities to send near-real time price information so that consumers may consider energy conservation during peak hours to reduce bills and control carbon dioxide emissions. Also AMI will enable demand management functionality in order to meet user demand in near real time. Moreover near real time prices could be communicated to user equipment via HEMS. These price signals would then be used to make consumption adjustments based on learnt user preferences. Such an advanced control system requires suitable communications networks both at user premises and to connect utilities and consumers. Above mentioned applications are summarized in Fig. 4. AMI can be thought of as one of the

modern grid milestones along with advanced distribution system, advanced transmission system and assets integration.

Smart meters in a neighborhood are linked to data collectors which serve as central units. Together they form a NAN. In theory, these data collectors can be either part of smart meters or separate devices. Every data collector is linked to an AMI Wide Area Network or backhaul through a collection point. All this data is provided to a management application at a server at the utility end [13]. Alternatively distributed management application at multiple servers may be employed. A NAN has a coverage distance of a few square miles. It requires bandwidth of the order 100–500 kbps (depending on desired data services) and bi-directional communications. Latency requirements for NAN are between 1 and 15 s [17].

Typically AMI requires infrequent uplink transmissions with small packet sizes leading to low bandwidth requirements for individual consumers (overall requirements increase considerably due to a huge number of customers) and are latency tolerant. AMI systems typically use a communications interval of 15 min to once per hour [17]. Broadcasting and multicasting support helps to avoid sequential meter reading in AMI networks [28]. Potential privacy and security problems are associated with communications of metering data wirelessly. Consumption information is a good indicator of consumer's daily activities and the presence or absence. Therefore like similar internetworking systems AMI is vulnerable to security threats [43] and there is need for end-to-end encryption to provide confidentiality of metering data [44].

Electricity theft and non-technical losses is another important issue of the power system distribution. AMI can help in detection and reduction of electrical theft issues as well. Anas et al. [45] have reviewed electricity theft and detection issues using AMI and showed the reduction in non-technical losses through MATLAB simulations. A comprehensive review of the issues, challenges and advantages of smart meters and AMI has been carried out in [46] which covers various technologies and features that can be included in smart meters. The authors have also mentioned design, implementations and utilization challenges about AMI.

4.2. HEMS

In energy sector, dynamic demand control is needed in order to save cost for utilities and the consumers. Moreover consumers have become more conscious about energy efficiency and want to be aware of real time energy consumption and to be a part of its effective management. Furthermore, increasing trend towards smart home appliances/devices necessitates reliable energy. At the same time, in many countries including Pakistan, there is a need of selective load shedding or Direct Load Control (DLC) upon the basis of the fair and implementable loads selection criteria in order to solve the recent energy crisis. Implementation of this DLC mechanism is subjected to the provision of HEMS to be placed in the user premises. The interaction of HEMS with various smart entities is indicated in Fig. 5.

Basic theme is to be aware of energy usage at any time and to control energy flow in order to achieve benefits such as saving money, automation, remote central control etc. The information flows from appliances to HEMS through sensors and an efficient sensor network is required to achieve high reliability and performance. HEMS benefit both the utility and consumer by enabling energy supervision, monitoring and control. Its role is to intelligently monitor and control energy usage by interfacing to smart devices, smart appliances, smart plugs and smart meters as well as to provide peak load management.

The communications network connecting HEMS with the smart components at a certain premises is the HAN. A smart meter is intended for the basic functions so that it can operate for longer period of time and without any requirement of frequent software or hardware up gradation. For the complex operations, a separate HEMS is employed. HEMS provide a certain level of intelligence implemented in software that can reside on a dedicated hardware. Upgrading and installing new functions and protocols to an EMS is independent of smart meters. Advanced HEMS can also include other aspects of HAN such as security systems.

The consumers are benefited heavily from such a system as they can monitor the real time energy used by the individual appliances. Moreover they can compare energy efficiency of different appliances and control various appliances like air conditioning and ventilation systems, smart appliances and smart plugs etc. On the other hand, utilities also get benefited from HEMS as the peak load management can be employed using the available data. Dynamic demand response management, which is a desirable feature of smart grid system, can be integrated with individual household profiles using HEMS. Baig et al. have suggested a smart HEMS for smart grid using ZigBee sensors and an interface designed in LABVIEW [47]. Khan et al. [48,49] and Nadeem et al. [50,51] have reviewed the HEMSs and optimization techniques proposed in context of smart grid for effective DSM.

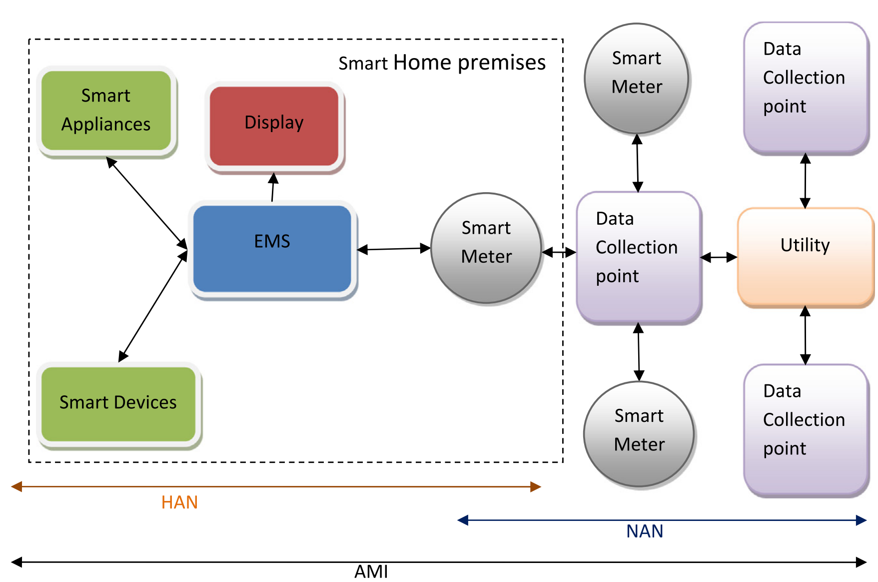

Fig. 5. Interaction of HEMS with various smart entities.

4.3. DA and DERs

Reliability of traditional power distribution systems can be significantly improved by employing real time monitoring and intelligent control systems. In such a smart system, sensors at various distribution components would transmit data (status, current, voltage, frequency etc.) via a suitable communication technology to a control system. The control signals by the control system would then control power supply and different quality parameters. Note that such control system can be centralized or localized/distributed.

Moreover, the smart grid will enable large scale integration of DERs with the electricity grid. The legacy power generation and transmission concept of large and far-off generation units providing power via lengthy cables, results in great losses in the form of heat. DERs can provide power in a more cost-effective and efficient manner from sites nearer to the customers. Such an integrated distribution system offers greater reliability and robustness as the backup is always available [52,43].

Integration of DERs with the electricity grid results in two way power flow in contrast to the traditional one way power flow. This creates some issues for the distribution network operators since the legacy distribution networks were static requiring no significant control or reconfiguration operations. However all DERs to be integrated into the smart grid would have an electronic power processor and switching power interface for controlling the exchange of power and currents with the grid [43]. Thus in a smart grid the distribution networks will be in a constant state of change depending on the amount and direction of power flow. This will require Energy Management System to embrace a more active approach rather than the traditional passive one so that the distribution network can be reconfigured depending on the power flow changes. Traditional control systems employed in industry like Supervisory Control and Data Acquisition (SCADA) can be modified to implement distribution management. Also, an active control system needs access to control information from the distribution network. Therefore, a great number of sensors will have to be deployed for monitoring of system conditions such as faults, status of switches and circuit breakers, sectionalizers and reclosers, power flow direction and magnitude. This would require a large transmission bandwidth and low latency so that control information is provided to the controllers quickly [52].

Active control also symbolizes a move towards a more distributed control configuration. Distribution networks are divided into small and separate entities called micro-grids each with an autonomous intelligent controller to manage it. These intelligent controllers receive sensor data and actuate control operations on the micro-grid level, thereby reducing computational load at the control room. The controllers of different micro-grids communicate among each other and run collaboratively to achieve better management [52]. Load classification is also an important aspect of the DSM and DA which is covered in [53]. A process model, consisting of five stages, is adopted for load classification in smart grid. Clustering methods for load classification have also been covered by the authors. Conceptual diagram for power flow, communication and control network integration for automation of distribution is shown in Fig. 6.

4.4. EVs

Current fossil fuel based transportation systems are a major source of greenhouse gas emissions. Zero-carbon EVs are becoming commercially practical due to recent advancements in fuel cell

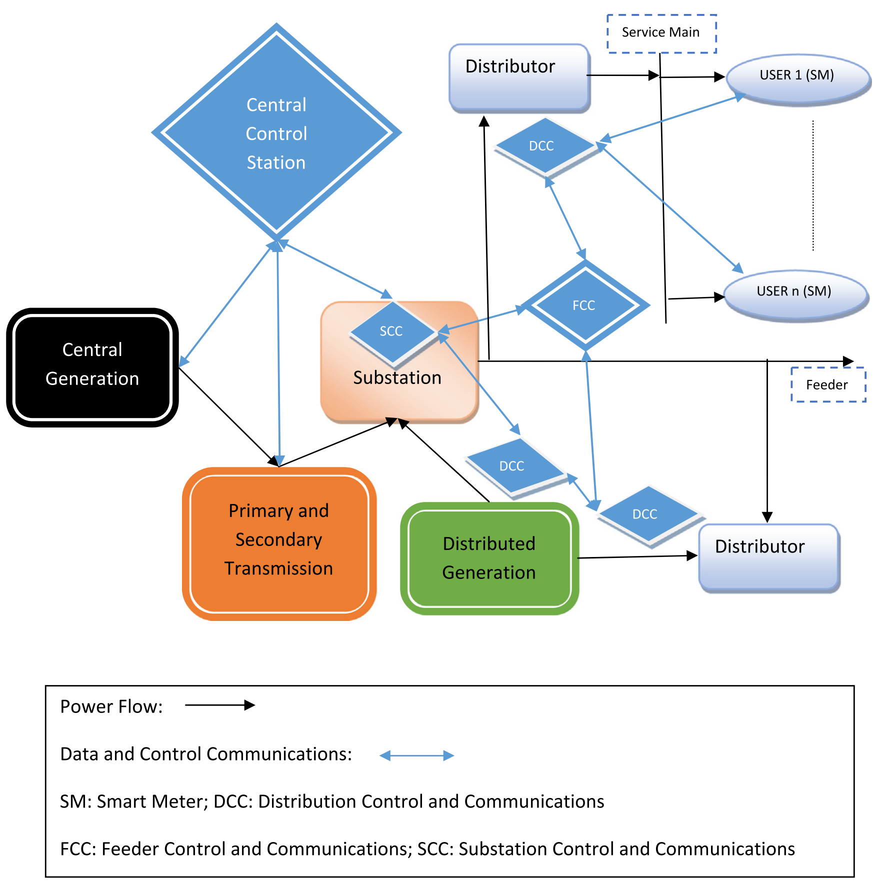

Fig. 6. Distribution automation with central control and DERs.

technologies [54]. EVs have significant potential to cut greenhouse gas emissions and fossil fuel imports. These economic and environmental gains are accompanied with challenges like enormous load growth and power quality issues such as frequency and voltage instabilities associated with large-scale EV integration with the electrical grid. For instance, if too many vehicles start charging during off-peak periods, when electricity prices are low, then violations of feeder thermal limits and distribution transformer capacity limits may take place. Similarly if many vehicles with vehicle-to-ground capabilities simultaneously release energy back to the grid by discharging their batteries (to take advantage of high prices) then the power system frequency may become unstable.

A special purpose EV management system is required to properly coordinate the charging and discharging process to avoid overload conditions of the grid. 'On-the-go' communications between EVs and the grid is essential because of vehicular mobility. Moving EVs transmit parameters like location, battery status, and charging and discharging demand to the EV management system which calculates real-time electricity price based on this information. Electricity prices then regulate the charging/discharging demand and power system stability is maintained [44,52]. Concept is elaborated pictorially in Fig. 7.

Only wireless communications can provide such information exchange. Existing cellular communications networks already provide required coverage for mobile vehicles. Communications costs can be reduced by using Vehicle Ad Hoc Networks (VANETs) and Vehicle-to-Infrastructure (V2I) communications related issues like handover and mobility support need to be handled properly [44]. The communications infrastructure should be secure, scalable, and reliable, have sufficient throughput with low latency for real-time behavior and be cost-effective. A common standard regulating charging process related communications is also required. Session Initiation Protocol (SIP) and the IEC 61850 protocol may be used for reliable, scalable and secure communications between EVs and EV management system [28].

Realization of smart grid will be accompanied with a lot of benefits for mankind, however still there are certain challenges and issues which are needed to be addressed. These challenges are briefed in subsequent section.

5. Challenges and issues

Conversion of conventional power system into smart grid is too much complex. Many kinds of challenges are being faced in this transformation process. Communications infrastructure, required for applications of smart grid, is found among major and the most important challenges. Continuous research is required to increase understanding of problems associated with smart grid communications requirements and to provide appropriate solutions. This section discusses the key issues and challenges to identify the main hurdles in implementation of smart grid.

Complexity: Smart grid will be very complicated system. Challenges like modeling, analysis and design of a smart grid including communications infrastructure are required to be addressed. The complexity of smart grids can be summarized in two main factors: the interdependence between different infrastructures and the distributed nature of monitoring and control functions.

Fig. 5 illustrates the communications and control complexity in smart grid systems while dealing with generation, transmission, distribution and consumer-end integration of all the systems in a common platform. Such a huge complexity is a major challenge in smart grid systems.

Efficiency: The smart grid system is supposed to be fully automated to get desired efficiency of the system. Infrastructure of smart grid is strengthened by the communication protocols that govern communications among various grid entities. These protocols must be optimized for various smart grid applications. Requirements to achieve high efficiency of the system are: accurate time measurements, faster control messaging, integrated communication devices, enhanced computing and appropriate network topologies.

Consistency: A very common challenge faced in smart grid is consistency of the system. Most of the smart grid applications depend heavily on the underlying communications infrastructure. A persistent communications system results into persistent grid actions. For instance, the communications among consumer-end devices (EMS smart meter etc.) and utilities/energy providers will result in consistent demand response, quality monitoring, and disaster/outage management etc. Moreover, a robust communications infrastructure is required to tackle disasters and power outages etc.

Security: One of the major challenges involved in smart grid is communications security. As the smart grid is an interlinked network, any cyber security breach can potentially expose the whole system. The system involves interconnection of various domains such as power plant, consumer end, substation and information technology domains. Each domain individually as well as whole system should be fully secured. Countless efforts are needed for provision of secure interlinked smart grid communications network. Many of the researchers are in pursuance to get enhanced security of smart grid as well as many organizations worldwide are working on developing better solutions for smart

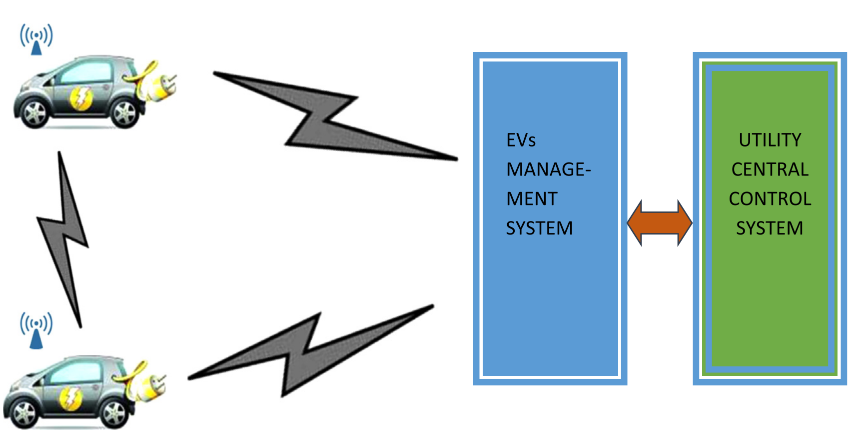

Fig. 7. EVs management system.

grid security including IEEE, International Society of Automation (ISA), North American Electrical Reliability Corporation-Critical Infrastructure Protection and the US National Institute of Standards and Technology.

Standardization: Smart grid includes different standards like power generation and distribution, communications infrastructure, data management, power control and monitoring etc. IEEE has defined the guidelines and standards for operation of smart grid using advanced technologies in electrical engineering, ICT and power control. Communications standards are arguably most important as most of the smart grid applications are communications dependent. Researchers are working on communications standards related to power distribution systems DERs, transmission substations, consumer requirements and network security. Work is also under way on the operational necessities of interoperability, scalability and all other factors to set common standards worldwide for smart grid. Other standardization bodies include International Society of Automation (ISA) and International Electro technical Commission (IEC). For instance, IEC TC57 WG13 drafted the new international standards for enhanced grid reliability as well as for cyber security [55].

Scalability: Smart grid communications infrastructure requires scalability of the system to accommodate more and more devices in order to serve new end-users. A scalable communications infrastructure for smart grid that uses 'one to many' and 'many to many' communication schemes is presented in [56]. The authors evaluated the proposed schemes in terms of delays and bandwidth usage. A scalable communications strategy has also been presented in [57] that uses data-centric application platform for smart grid. Scalability is particularly important in the AMI context as hundreds of thousands of meters need to communicate to energy provider and the number of such meters keeps on increasing. Also with the passage of time, frequency of data transmission between users and utilities will increase. Li et al. [58] presented scalable communications architectures for smart grid AMI and investigated the communications complexity and scalability of the proposed system. The authors formulated optimization problems in order to find minimum cost in terms of bandwidth and distance incorporating scalability of the system.

Interoperability: It refers to the ability of various systems or components to work/communicate with each other in a smooth manner. Many organizations have worked on smart grid interoperability issues. For instance, the US National Institute of Standards and Technology (NIST) has proposed a model of interoperability for smart grid in [59]. Different domains of smart grid like generation, transmission, distribution, customers, operations, markets and Independent System Operators (ISO) are needed to be interoperable and compatible from older to the newest versions to ensure successful operations. This is very important aspect of the smart grid that poses huge challenges [60,61].

Self-healing actions: Handling a system during abnormal conditions or under fault is much more complex as compared to the normal operation. That is why a key challenge for the implementation of smart grid is encountered while defining the system under contingency. The system needs to respond immediately to avoid system breakdown and must start self-healing actions within a small period of time after any contingency. Fast control signaling is a fundamental requirement in such situations in order to control various actuators in the system.

Continuous monitoring through sensors and appropriate actions to prevent faulty conditions is an important aspect of the smart grid. However, enabling system to self heal after occurrence of the fault requires enormous automation, fast control and integration of the artificial intelligence at each level. Isolation of the faulty part of the system to avoid spread of fault is fundamental requirement of the protection system. Reconfiguring the faulty part after self healing in accordance to the system conditions without manual interruption is a big challenge for smart grid. Various challenges and issues of smart grid with important aspects are tabulated in Table 3.

Table 3
Aspects of different challenges and issues of smart grid.

Challenge/issue	Aspects
Complexity	• Modeling, analysis and design of smart grid • Interdependence between different infrastructures • Distributed nature of monitoring and control functions
Efficiency	• Optimization of network parameters • Accurate time measurements • Faster control messaging • Integrated communications devices • Enhanced computing • Appropriate network topologies
Consistency	• Consistent demand response • Quality monitoring • Robust communications infrastructure required to tackle disasters and power outages etc.
Security	• Interconnection of various domains • Ease of security breach in user premises • Virus and hacking attacks
Standardization	• Design, development and provision of common standards worldwide • Uniformity among various standard organizations • Regional and international concerns
Scalability	• Accommodation of more and more devices like smart meters • Bandwidth adjustments according to additional users
Interoperability	• Ability of various systems or components to work with each other in a smooth manner • Different domains of smart grid like generation, transmission, distribution, customers, operations, markets and Independent System Operators are needed to be interoperable and compatible from older to the newest versions
Self healing	• To avoid system breakdown • Must start self-healing actions within a small period of time after any contingency • Fast control signaling

6. Conclusions

Exploitation of enormous potential of smart grid, for wellbeing of mankind, is dependent upon the rapid development of advanced communications infrastructure and optimization of network parameters. We have reviewed the WCTs for HANs and NANs separately and compared them in context of consumer concerns and utility requirements. Wi-Fi offers high data rate and larger range (100 m indoor) as compared to Bluetooth short range (10 m typical) secure communications, but ZigBee with low cost, low power consumption, reasonable indoor range (10–75 m) and ability of accommodating a very large number of nodes seems to be the best candidate for HANs. Low data rate of ZigBee (40–250 kbps) is one of the reasons it is a low power technology. Although ZigBee data rate is much less than Wi-Fi (11–300 Mbps), it is good enough for most of the usual HAN applications. Furthermore ZigBee supports a high number of nodes (more than

64,000) which makes communications scalable when new nodes enter the system. Z-Wave and 6LoWPAN are advantageous for IP enabled low power devices. Bandwidth and the range of WiMAX make it appropriate for smart grid NANs applications. WiMAX offers 72 Mbps speed which is 36 times greater than typical 3G GSM speed. On the other hand, pre-existing cellular networks with sufficient bandwidth, high data rates (more than 300 Mbps for 4G LTE), extensive coverage, lower maintenance costs and strong security can save capital investments on utility dedicated communications infrastructure and allow rapid deployment of applications. However, use of pre-existing cellular networks will raise the operational cost in terms of monthly recurring charges. A dedicated utility cellular network can ensure the high quality and reliability with reduced operational cost. There exists a clear trade-off when making a choice between dedicated WCTs like WiMAX and pre-existing technologies like GSM cellular network. This choice essentially depends on a particular utility's budget and policies. This comprehensive review has tabulated different wireless communications in a systematic way along with the challenges for smart grid implementation.

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